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INVESTIGATIVE RESEARCH ON THE EFFECT OF ZERO-MASS JETS ON THE BASE DRAG OF AXISYMMETRIC BODIES AT SUPERSONIC SPEEDS

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1. INTRODUCTION

For axisymmetric aerodynamic bodies in supersonic flight, the flow field in the wake region has considerable effect on the aerodynamic drag. Even small changes in the flow behavior of the wake may affect the performance of the entire flight vehicle, e.g., missiles, rockets, or projectiles. The effect on the aerodynamic drag is mainly due to the recirculation region that develops in the base region of the body and thus to the low pressure associated with the recirculating flow ("base drag"). Flight tests with projectiles (U.S. Army 549 projectile) have shown that the base drag may account for up to 35% of the total drag (Rollstin 1987). This suggests that attempts to modify or "control" the near-wake flow such that the base pressure would increase could be highly rewarding with respect to drag reduction and, as a consequence, with regard to increasing the performance characteristics of flight vehicles or projectiles.

In recent years, many experimental efforts have focused on modifying or "controlling" the base flow in order to reduce the base drag. So far, only "passive control" methods have been considered, such as *boattailing, base bleed, base burning,* and *base combustion* [see, for example, Cortwright and Schroeder (1951), Reid and Hastings (1959), Bowman and Clayden (1968), Clayden and Bowman (1968), Valentine and Przirembel (1970), Hubbartt et al. (1981), Sahu et al. (1985), Ding et al. (1992), Nietubic and Gibelung (91993), Sahu and Heavey (1995), and Mathur and Dutton (1995, 1996a,b)]. These experiments have shown that there are potentially considerable rewards for flow control. However, it is still not understood why certain measures are more effective than others (or why others do not work at all) and what the "optimal" parameters should be. The reason for this is that the fundamental physical mechanisms are not yet understood.

2. TECHNICAL BACKGROUND

2.1 Large-Scale Coherent Structures

It is well known that for subsonic (incompressible) wakes, the dynamics of the large (coherent) structures play a dominant role in the local and global behavior of the flow. This evidence was found from both experimental investigations and numerical simulations (including ours) and was confirmed by theoretical studies. For incompressible bluff bodies, it has been well established that the existence of absolute and global instabilities is responsible for the development of the large structures (Huerre and Monkewitz 1990). Using numerical simulations, absolute/global instabilities were found for a two-dimensional bluff body with a blunt base by Hannemann and Oertel (1989) and for an axisymmetric body with a blunt base by Schwarz et al. (1994). The absolutely/globally unstable modes for the axisymmetric base are of a helical nature.

For supersonic speeds, on the other hand, relatively little is known about the dynamical behavior of the large structures in turbulent flows or, in particular, if absolute/global instabilities exist. This is true for supersonic flows in general and for axisymmetric wakes in particular. The explanation for this void is that experiments are difficult to conduct for supersonic speeds (see discussion in introduction). In addition, expensive facilities and intricate diagnostic equipment are required for supersonic hydrodynamic stability experiments.

Due to the lack of guidance from experimental investigations prior to our research initiative on the subject, no successful computational/theoretical attempts have been made to study the unsteady, dynamical behavior of transitional or turbulent supersonic axisymmetric base flows. We feel that, as for subsonic wakes, it is exactly the dynamical behavior of the large-scale structures that strongly influences the flow field in supersonic axisymmetric wakes and, as a consequence, base drag. Thus, if the evolution and development of the large-scale structures could be modified or "controlled," the base drag could be reduced.

As in the subsonic case, supersonic wake flows behind a blunt base are dominated by a separated region, and associated with it is an axisymmetric shear layer originating from the sharp corner of the base. Turbulent, subsonic (incompressible) shear layers are characteristic of developing large, coherent, turbulent structures that are of a highly unsteady nature. (For two-dimensional shear layers, these large structures are strongly two-dimensionally organized.) Thus, it is not surprising that large coherent structures, which can be observed to originate in the shear layers directly behind the blunt base, are present also for subsonic turbulent wakes behind blunt trailing edges.

There is considerable evidence that the cause of the large structures is due to the hydrodynamic instability of the (time-averaged) mean flow and that the development of these structures can be

captured by stability theory. In fact, certain aspects of the development can be captured even with linear stability theory, although intensities (amplitudes) of the structures are often too large for the linear stability theory to be valid. Experimental results for incompressible turbulent mixing layers, two-dimensional turbulent wakes, and axisymmetric wakes with a blunt base and comparison with linear stability theory have shown that certain key features, such as dominant frequencies, mode shapes (amplitude distributions), and streamwise spacing (streamwise wave lengths) of the structures can be well predicted by linear stability theory (Wygnanski et al. 1986; Marasli et al. 1989). These investigations support the notion that hydrodynamic instabilities give rise to the generation and development of large structures.

The dynamical behavior of these structures is responsible for the strong unsteady flow behavior in the wake. Thus, in reality, there is no "steady" turbulent wake flow, even when the small-scale (high-frequency) fluctuations are not taken into consideration. Rather, the flow is highly unsteady, dominated by large-amplitude and, relative to the small scales, low-frequency fluctuations. The "steady" mean flow measured in experiments is in fact the time average of the time-dependent fluctuating flow field. Since the amplitude of these large-scale fluctuations can be relatively large, the total flow field cannot actually be composed by linear superposition of the various fluctuating components onto the ("steady") mean flow field. Rather, because of nonlinear interaction between the various fluctuation components, the actual mean flow may be strongly dependent on the composition of the fluctuating parts of the flow field.

This evidence was confirmed experimentally for incompressible wake flows (Wygnanski et al. 1986, Marasli et al. 1989) by artificially forcing the flow. With artificial forcing, existing modes (structures) could be modified or new modes (structures) created. As a consequence, the mean flow could be modified substantially. This study showed convincingly that there is no unique turbulent mean flow for the wake and not even for the far wake. Rather, the mean ("steady") wake flow is strongly dependent on the nature of the large-scale coherent structures and, as a consequence, on their dynamical behavior.

Relevant to the present research is the question: Do large structures play a similarly important role for supersonic separated flows and in particular for supersonic axisymmetric wakes? For planar supersonic shear layers, the experimental investigations of Papamoschou and Roshko (1988) have convincingly demonstrated a dominant presence of large-scale structures for a large variety of conditions, e.g., Mach numbers and density ratios. In fact, relative to the shear-layer thickness, these structures are often considerably larger (and therefore appear to be more dominant) than those for incompressible shear layers. Large-scale (coherent) structures for supersonic shear layers were also observed by Ortwerth and Shine (1977) and for supersonic jets by Oertel (1979). For the supersonic

axisymmetric shear layer behind a backward-facing step investigated by Roshko and Thomke (1966), flow visualization suggests a mean flow that is predominantly periodic in the azimuthal direction, indicating possibly the presence of large (coherent) structures with a dominant azimuthal wave length [see Figure 6 in Roshko and Thomke (1966)].

Some quantitative evidence of the existence of dominant large structures in supersonic axisymmetric wake flows has been provided by the experiments of Demetriades (1968), who investigated the unsteady nature of the flow field. The amplitude spectra (see Figures 11 to 14 in Demetriades) display distinct peaks at certain (relatively low) frequencies, thus indicating the presence of dominant modes (structures). This is supported by plots of rms-amplitude distributions (with respect to radial distance from the centerline) for the axial velocity fluctuation and the density fluctuation (Figures 2 and 3, respectively, of Demetriades). The amplitude distribution for the velocity fluctuation is highly reminiscent of that of an incompressible axisymmetric wake, where it is known that this profile is due to the presence of dominant, large coherent structures (Cannon 1991). In fact, Morkovin (1968) suggested long ago that when normalized properly, the distribution of fluctuations (as caused by large structures) has a universal character, even in very diverse flow regimes, e.g., even when comparing subsonic and supersonic flows.

More recently, at the University of Illinois, Dutton [see, e.g., Smith and Dutton (1996)] identified coherent structures for a supersonic two-dimensional wake behind a blunt base. The observed dominant structures appear to be very large relative to the shear layer thicknesses. These observations are in qualitative agreement with those of Papamoschou and Roshko (1988) for a planar supersonic shear layer. From our previous numerical investigations of transitional and turbulent base flows (two-dimensional and axisymmetric), we found highly energetic structures with amplitudes of about 15% of the free stream velocity that have a significant effect on the global flow behavior. Therefore, our previous simulations and the experiments by Dutton and co-workers indicate that large coherent structures may indeed play an important role in supersonic wake flows and, in particular, in supersonic axisymmetric base flows. The fact that dominant structures can exist in axisymmetric wake flows is crucial to the proposed research on using zero-mass jets to modify the mean flow behavior.

2.2 Modification/Control of Shear Flows

Numerous attempts have been reported in the literature on the modification ("control") of shear flows. However, most of these investigations were for incompressible, or at least low subsonic, flows. Exceptions are the investigations on modifying axisymmetric base flows carried out at the Army Research Laboratories (Sahu et al. 1985, Danberg and Nietubicz 1992, Nietubicz and Gibeling 1993, Sahu 1992). For incompressible wake flows, various control techniques were suggested, geometric

[for example, changing the shape of the surface or using appendages (such as splitter plates)], blowing and suction through surfaces, surface heating or cooling, etc. Also, an entirely different approach to flow control suggested in the literature is to "force" the flow by introducing time-dependent (typically periodic) perturbations using mechanical, acoustical, thermal, or other disturbance sources.

For the sake of clarity in the subsequent discussion, we will group the various control strategies into two categories: (I) Passive Control and (II) Active Control. According to our categorization, the first group of control techniques mentioned above, namely, change of wall geometry, blowing/suction, and wall heating/cooling, would fall into category I (Passive Control), while time-dependent forcing of the flow would fall into category II (Active Control). It should be pointed out, however, that in the literature often different definitions are used for passive/active control. We chose this classification based on physical arguments, as we believe that mechanisms of control can be discussed and to a large extent explained within the context of hydrodynamic stability theory.

As discussed in the previous section, there is considerable evidence that the evolution and dynamical behavior of the large (coherent) structures in turbulent shear flows can be described/modeled by hydrodynamic stability theory, although, of course, the linear stability theory is often not sufficient and has to be amended by nonlinear concepts. We define "passive control" to include all possible means that attempt to directly modify the mean flow such that the stability characteristics of the mean flow are changed and, as a consequence, the evolution and the dynamics of the resulting coherent structures are altered indirectly. The altered dynamical behavior of the large coherent structures would then in turn influence the global mean (time-averaged) flow behavior. Modification of the mean flow using passive control could either be in a time-independent or "slowly time-varying" manner ("slowly time varying" in the sense that the time scale of the variation of the mean flow is much larger than that of the large turbulent structures). For wake flows, examples reported in the literature of successful methods to modify the mean flow (and thus are suggested for passive control) are: (a) by geometric modifications using splitter plates (for two-dimensional incompressible wakes) or other appendages, or "boattailing" (for incompressible and compressible/supersonic wakes); (b) by blowing and suction for separation control of boundary layers (both laminar and turbulent), transition control of boundary layers, and base bleed (blowing) for bluff body wakes, including supersonic axisymmetric wakes [for supersonic wake flows, see discussions by Cortwright and Schroeder (1951), Reid and Hastings (1959), Valentine and Przirembel (1970), and Mathur and Dutton (1995, 1996a,b)]; (c) by wall heating and cooling (e.g., transition control of boundary layers) and "base burning," (heating) in supersonic axisymmetric wakes (Hubbartt et al. 1981; Ding et al. 1992).

In spite of numerous examples of "successful" passive control cited in the literature, the research findings are often controversial as the "success" of the various strategies appears to be strongly dependent on the specifics of the experimental setups. Slight changes of experimental conditions often lead to very different results. Also, the research was often carried out by a trial-and-error approach, without a deep physical understanding of the underlying mechanisms. As a consequence, to date, it is often still not understood why certain strategies work and what the control parameters should be even for relatively simple geometries (for example, the velocity distribution for base bleed). We believe that a much better understanding of the physical mechanisms and theoretical concepts is required in order to improve the chances of effectively controlling complicated wake flows.

From research efforts employing flow control for flows that are convectively unstable, such as wall boundary layers (both subsonic and supersonic), it is known that passive methods can be effectively used for modifying the flow behavior (for example, by using wall heating/cooling) to delay transition (Kral and Fasel 1990, 1991, 1994). For passive control of subsonic (incompressible) wake flows, the fact that regions of absolute/global instability can exist downstream of the base is crucial for devising effective means to modify the flow. As discussed in §2.1, absolute/global instability can lead to large amplitude (nonlinear) oscillations and, as a consequence, to the formation of large organized flow structures. Based on past research by others and us (including our water tunnel experiments and numerical simulations investigating the effects of splitter plates, base blowing etc.), the effectiveness of passive control of wake flows (to reduce drag, for example) is due to the fact that the absolute/global stability behavior is altered. As a consequence, the formation of high energetic vortical structures is inhibited or delayed to farther downstream. The fact that the stability behavior, and in particular the absolute/global stability behavior, is very sensitive to changes of the mean flow velocity profiles (i.e., minute changes of mean velocity profiles can cause large changes in the stability behavior) may explain the often puzzling and contradicting experimental results of wake flow control using passive methods. On the other hand, the fact that often only very small changes are required to cause drastic differences in the stability behavior suggests that relatively little effort in the design or operation of passive control methods may be required if executed optimally. However, to be successful in this respect, the physics of the local/global instability mechanisms have to be better understood than they are today.

For supersonic axisymmetric base flows, our past research has shown that absolute/global instability probably exists for the Mach numbers and Reynolds numbers that are of interest to the Army. But, even if the role of absolute/global instability were of lesser importance than for incompressible bluff body wakes, passive control could nevertheless be effectively applied to affect the convective instability behavior. In this case, passive wake control might even be easier to

implement. Furthermore, passive methods could be used in combination with "active control" methods to cancel or modify the flow structures that survived the passive control.

In contrast, for "active control," the mean flow is not directly modified, i.e., the hydrodynamic stability behavior is not altered directly. Rather, the naturally occurring time-dependent perturbations in the flow (for turbulent flows, the large structures) are attacked directly by introducing forced time-dependent perturbations into the flow. For example, for "active" transition control, the naturally occurring time-dependent disturbances, the so-called Tollmien-Schlichting waves that precede the transition process, can be canceled by locally introducing counter-disturbances with a 180° phase shift. Such active control can be used to delay transition. This was demonstrated experimentally by Liepmann and Nosenchuck (1982) and Liepmann et al. (1982) and in direct numerical simulations by Kral and Fasel (1990, 1991, 1994).

For turbulent free shear flows, where the large (coherent) structures have significant amplitudes and therefore the mechanisms are strongly nonlinear, the wave/superposition strategy, used in transition control (see above) where amplitudes are very small initially, is no longer applicable. In addition, for wakes behind bluff bodies (blunt base), regions of absolute instability (Huerre and Monkewitz 1990) exist (even for the laminar case) that lead to large amplitude (nonlinear) oscillations, which would prohibit the use of wave-canceling strategies. However, such flows can still be effectively altered by forcing. If the forcing amplitudes are large enough so that nonlinear perturbations are produced that can then (nonlinearly) interact with the existing (natural) large amplitude perturbations, i.e., the large structures, the mean (time-averaged) flow can be substantially modified. This was demonstrated convincingly in the experiments by Cohen and Wygnanski (1987a,b) where a jet with a circular cross-section nozzle was significantly altered by periodic forcing such that square, triangular, or other shaped cross-sections of the mean flow could be produced. Periodic forcing was also used effectively to modify (incompressible) turbulent mixing layers (Weisbrot and Wygnanski 1988, Wygnanski and Weisbrot 1988) and turbulent wakes, both two-dimensional and axisymmetric (Wygnanski et al. 1986; Marasli et al. 1989).

More recently, Wygnanski and his co-workers have shown experimentally that periodic forcing can be effectively used for control of separation of flows around airfoils, including control of dynamic stall (Wygnanski 1994). Currently, Seifert, Wygnanski, and co-workers are setting up experiments to investigate this approach for compressible (yet subsonic) flows.

From these and numerous other experiments, it is obvious that active control has considerable potential for control of separated and free shear layer type flows. However, there are often puzzling and unexpected results because the fundamental mechanisms responsible for control are still far from understood—which is not surprising since, as discussed above, the mechanisms are strongly nonlinear.

For supersonic flows, in particular for the axisymmetric base flows considered here, no successful investigations of active control are known to the author of this proposal. Obviously, laboratory experiments are considerably more difficult than for low-speed (incompressible) flows because the forcing has to be at extremely high frequencies and amplitudes to be effective.

3. RESEACH ACCOMPLISHMENTS

With funding from the present short-duration grant, we initiated an investigation regarding the modification/control of axisymmetric wakes using zero-mass jets emanating from the base. The jets are produced by high-frequency oscillations at the base (created by blowing and suction). The proposed strategy of using zero-mass jets that are generated by high-frequency forcing (for example, by blowing and/or suction) is between "active" and "passive" control. According to the classification used here, it is "active" in the sense that time-dependent forcing is employed. However, since its main effect is on modification of the mean flow, which in turn directly affects the stability characteristics, it can also be considered "passive." For the investigation, we employed Direct Numerical Simulations (DNS). Toward this end, we had to make major improvements/modifications to our existing Navier-Stokes codes for supersonic base flows. These modifications have been completed successfully and the modified code has been extensively tested and validated. In addition to investigating the effect of zero-mass jets in wakes behind an axisymmetric body, we also investigated their effect on wakes behind a two-dimensional body with a blunt base.

Before beginning the investigation of zero-mass jets for supersonic flows, we first wanted to understand—in detail—the physical mechanisms of the effectiveness of zero-mass jets for subsonic flows for which practically all of the investigations were carried out. From our simulations using DNS, we found that, for low subsonic (incompressible) two-dimensional and axisymmetric wakes, zero-mass jets can significantly alter the evolving flow structures in the wake and may even make the structures disappear entirely. From the discussion in §2.2, and our numerical simulations that clearly show the striking effect of the large structures on the base pressure, it is clear that effective flow control is directly linked to the ability to influence/modify the development and the dynamical behavior of the large (coherent) structures. Thus, if the large structures are weakened or the development of the structures is delayed to farther downstream, the base drag could be drastically reduced.

3.1 Numerical Results for Two-Dimensional Base Flow

For a Mach number $M = 0.2$ and $\mathrm{Re} = 400$, typical results of simulations of high-frequency, zero-mass jets are shown in Figures 1-2. At this Mach number, compressible effects can be considered small. Figure 1 displays results of a DNS for a two-dimensional wake flow that is forced by high-frequency blowing suction at the base, which results in a zero-mass jet emanating from the base. Shown are instantaneous vorticity contours at different times after the periodic forcing was turned on (Figures 1b-1c). For reference, the high-frequency forcing was not turned on for the instantaneous vorticity contours that are shown in Figure 1a. These results demonstrate how effectively the naturally

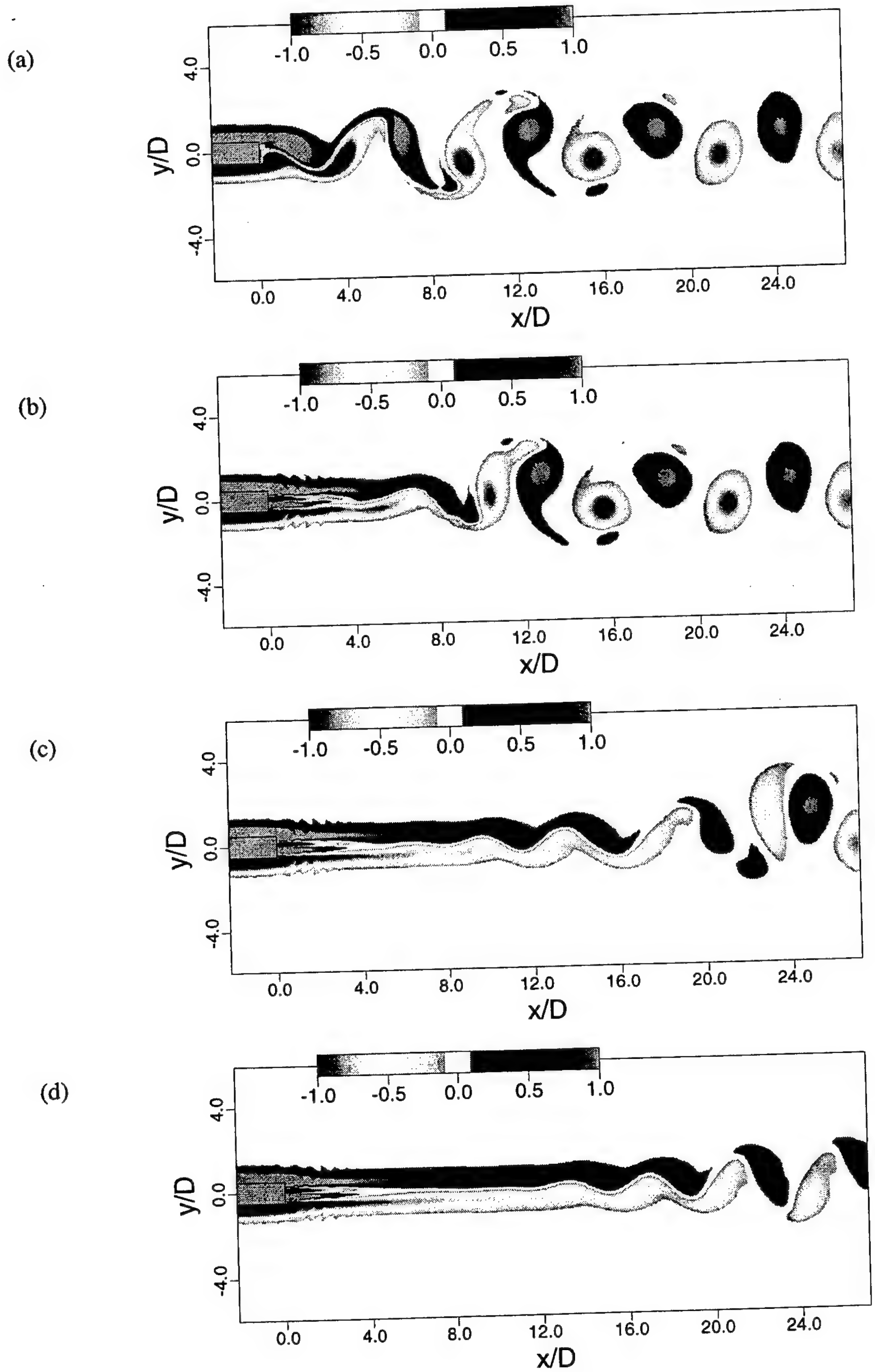


Figure 1. Instantaneous spanwise vorticity for two-dimensional wakes ($M = 0.2$) forced by high-frequency periodic blowing and suction at the base: (a) reference case, forcing off; (b)-(d) at different times after forcing is turned on.

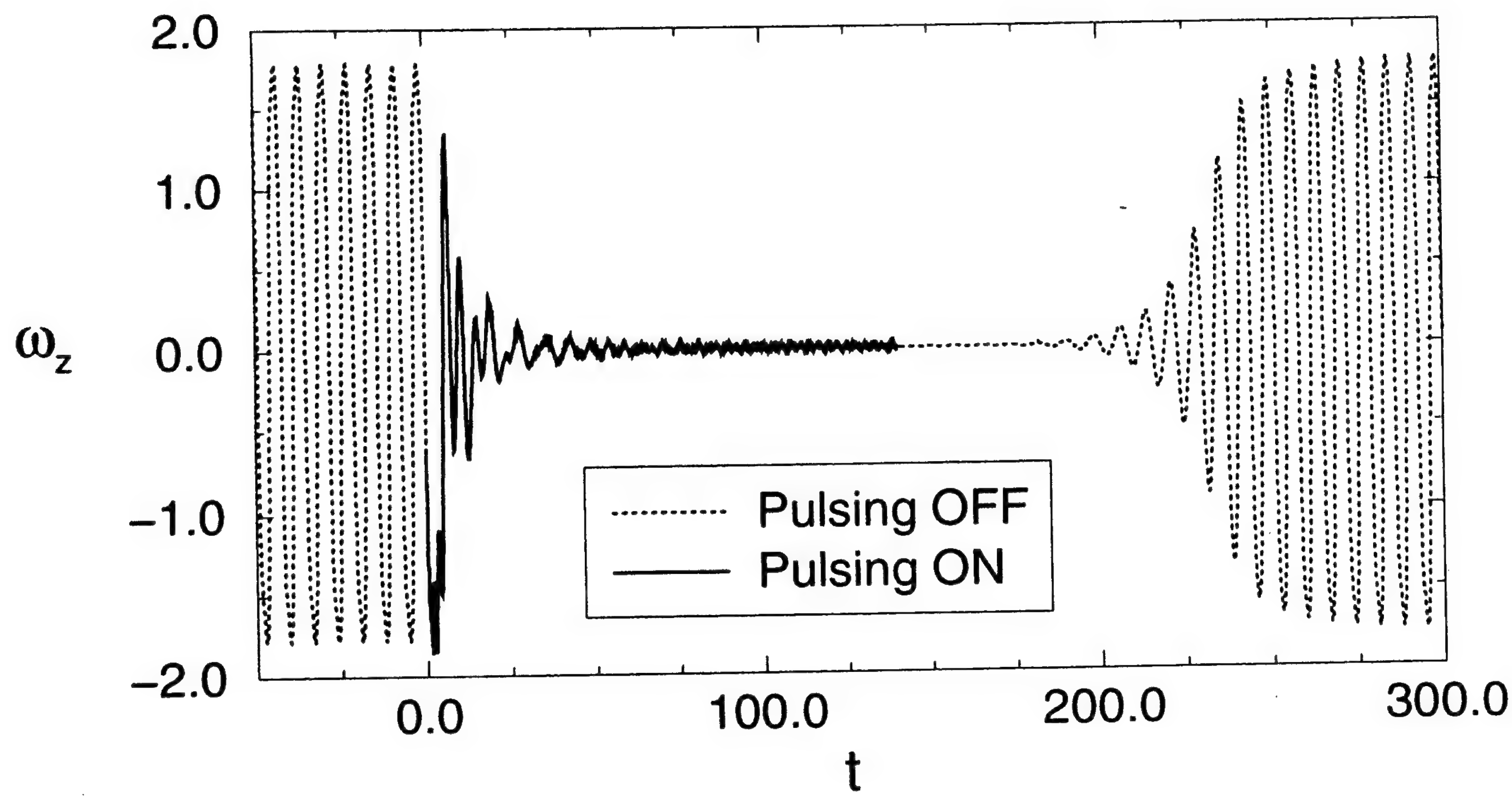


Figure 2. Spanwise vorticity at centerline downstream of the base versus time for two-dimensional wake forced by high-frequency flowing and suction at the base. Effect of turning forcing on/off.

present, highly energetic structures can be suppressed by the high-frequency forcing. The dramatic effect of the zero-mass jet is also displayed in Figure 2, where the spanwise vorticity at a representative downstream location from the base is plotted versus time. Immediately after the "pulsing" (periodic forcing) is turned on, the amplitude of the wake structures decays rapidly and the flow becomes almost steady. If the pulsing is then turned off, the wake oscillations quickly return to their original amplitude level.

To investigate if the dramatic effect of high-frequency, zero-mass jets persists in the presence of compressibility, simulations were carried out for higher subsonic Mach numbers and even supersonic Mach numbers. For higher subsonic Mach numbers, the effect of zero-mass jets was similar to the low subsonic cases. However, with increasing Mach number, the required frequencies also increased. Even for supersonic Mach numbers, periodic pulsing proved effective. Typical results of such calculations from a simulation with Re = 2000 and $M = 1.2$ are shown in Figure 3 in the form of contours of spanwise vorticity. Figure 3a is for the "natural" wake without forcing. Figures 3b and 3c are for time instances after the pulsing has been turned on. Figure 3b, which is for a time instance shortly after the pulsing has been turned on, indicates a rapid decay of the vortex shedding motion. The wake becomes completely stable and steady (Figure 3c) after the pulsing has been on for a sufficiently long time so that all unsteady vortex structures have been convected downstream and out of the domain of interest.

3.2 Numerical Results for Axisymmetric Base Flow

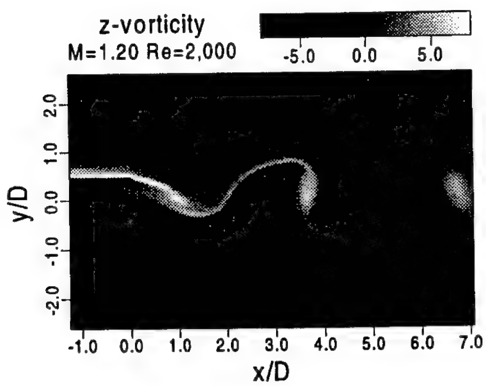
Next, we turned our attention to investigating the effect of high-frequency forcing (zero-mass jets) on the wake structures behind an axisymmetric body with a blunt base. Simulations with a Mach number $M = 0.2$ and Reynolds number $\mathrm{Re}_D = 1000$ were carried out. The disturbances were generated through a blowing and suction slot located at the base of the bluff body. Two different setups for the disturbance slot were used for this investigation (Figure 4). The velocity distribution for the centered jet has the form

$$u(r) = A\cos^2\left(\frac{r}{r_{\max}}\pi\right)\sin(\omega t) \tag{1}$$

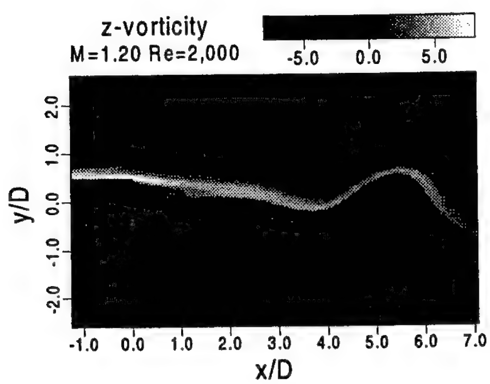
while the form for the annular jet is

$$u(r) = A\sin^2\left(\frac{r - r_{\min}}{r_{\max} - r_{\min}}\pi\right)\sin(\omega t) \tag{2}$$

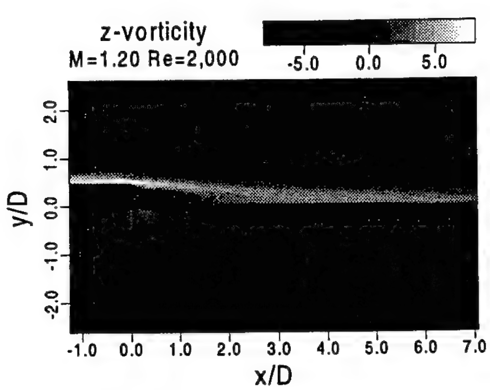
The three-dimensional flow field was initialized with an axisymmetric steady field and was disturbed with a local pulse within the flow field. Only the first azimuthal Fourier mode of the density was disturbed at a single point in space. The pulse had a duration of one time step and an amplitude of 1 percent of the free stream density.



(a) Pulsing (Zero-Mass Jet) Turned Off



(b) Time Instance After Pulsing (Zero-Mass Jet) is Turned On



(c) "Steady State" with Pulsing (Zero-Mass Jet) On

Figure 3. Instantaneous spanwise vorticity for two-dimensional wake (Re = 2000, M = 1.2).

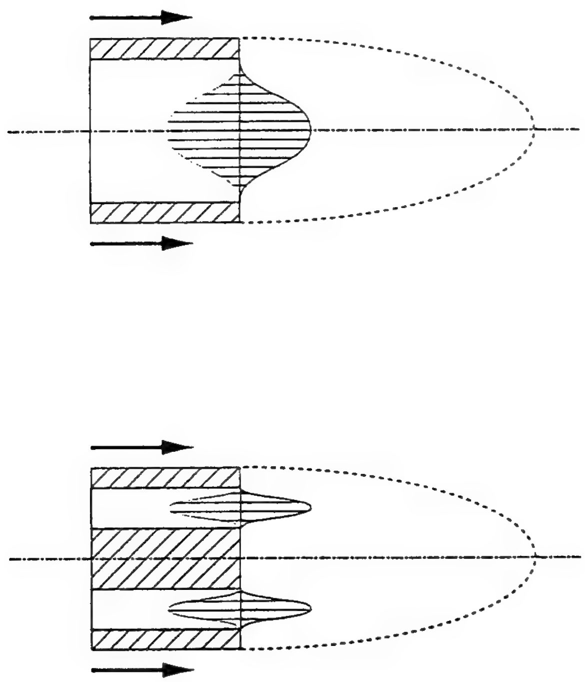


Figure 4. Illustration of high-frequency zero-mass jet generation in a bluff body wake (top: centered jet; bottom: annular jet).

This flow field developed into the typical *natural* unsteady wake flow. The *natural* flow field was then disturbed by high-frequency axisymmetric blowing and suction on the base. At the beginning of the calculation, the amplitude, A, was ramped up to its final value over two full periods of the disturbance by using an exponential function.

Amplitude changes during the calculation runs, however, were performed by a sudden change, which did not seem to cause any problems other than creating a large disturbance. This disturbance was convected downstream and eventually left the integration domain for all calculations. Also, frequency changes were performed by a sudden change during the simulations, which had an effect similar to the amplitude changes.

Even though there might be effects of three-dimensional disturbances that would be interesting to investigate, at this point, it is more important to test the basic applicability of zero-mass jets for the control of bluff body wakes. Therefore, only axisymmetric disturbances have been considered in this study. As a precursor to the three-dimensional simulations, the effect of high-frequency blowing and suction on a strictly axisymmetric flow field was tested. This investigation showed that the oscillations can alter the time-averaged flow. This alteration becomes stronger with high frequencies. In fact, hardly any change was observed for Strouhal numbers lower than $St_D = 3.5$. Therefore, the lowest Strouhal number chosen for this investigation was $St_D = 3.82$.

The results of all three-dimensional simulations can best be compared by watching a VHS video that we produced. The graphs presented in this report merely show representative instantaneous flow fields in order to demonstrate certain effects.

3.2.1 Case 1

For the first calculation, the Strouhal number was $St_D = 3.82$ and the maximum velocity amplitude of the blowing and suction was 200 percent of the free stream velocity (see Table 1). The disturbances were generated through an annular blowing and suction slot (see Figure 4). These disturbances had no effect on the behavior of the wake flow. Figure 5 shows a typical instantaneous flow field in the form of isocontours of total vorticity.

Table 1. Parameters used in the simulations.

Case No.	St_D	Amplitude	R_{min}	R_{max}
1	3.82	2.0	0.25	0.5
2	3.82	2.0	0.0	0.495
3	3.82	4.0	0.0	0.495
4	15.28	2.0	0.0	0.495
5	15.28	4.0	0.0	0.495
6	12.73	4.0	0.0	0.25

The structures that occur in the flow field have shapes and strengths very similar to the structures that can be observed in the undisturbed or *natural* flow field. A spectral analysis would most likely also show results very similar to those for the *natural* wake. Thus, it can be concluded that the flow field does not show any response to this type of disturbance. Since the annular disturbance did not show any significant response of the flow field, a centered jet disturbance generation was used in all the following simulations.

3.2.2 Case 2

The same disturbance amplitude and frequency as used in Case 1 were used in this simulation. Now, however, the disturbance was generated through centered blowing and suction covering almost the entire base. Figure 6 shows a typical instantaneous flow field in the form of isolevels of total vorticity.

The first difference that can be observed from Figure 6 is that two peaks of vorticity (with opposite signs) occur immediately downstream of the base. These two peaks resemble a cut through a

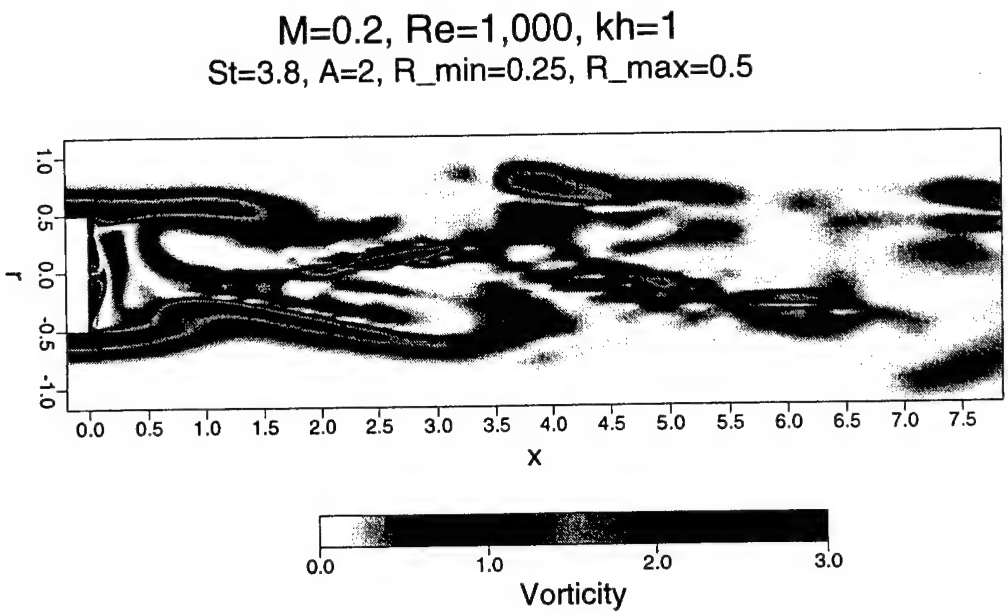


Figure 5. Isolevels of instantaneous total vorticity for case 1.

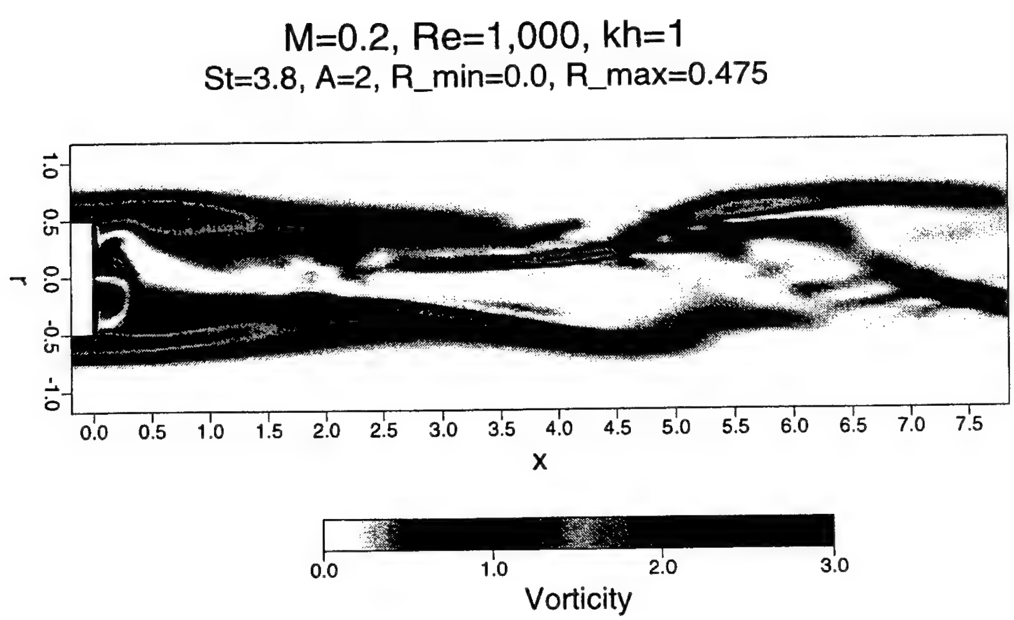


Figure 6. Isolevels of instantaneous total vorticity for Case 2.

vortex ring that was created by the disturbance generation. The plot also reveals that the structures appearing in the flow field farther downstream seem to be more regular than those in the *natural* wake. In addition, the vorticity peak within the structure reaches a lower level than was observed for the *natural* wake. This could be an indication that these structures are weaker than the ones observed in the undisturbed flow field.

3.2.3 Case 3

Because of the promising results for Case 2, the disturbance amplitude was raised to 400 percent of the free stream velocity. Figure 7 shows a typical instantaneous flow field in the form of isolevels of total vorticity. At first, it seems that the amplitude change does not have any significant effect on the flow field. After some time, however, stronger structures reappear that have a shape similar to the structures observed in the *natural* wake. A video animation reveals, however, that the structures appear more often than in the *natural* wake. It also seems that the vorticity within the structures reaches a stronger peak. Thus, there seems to be more disturbance energy in the flow field.

At this point, it was impossible to extract enough data from the simulation to calculate a time average of this flow field. But, the results suggest that the drag will probably be higher with this disturbance. Thus, the disturbance has a significant effect on the global flow field, even if it might not have the desired effect.

3.2.4 Case 4

Since there was no significant effect in the previous three cases, the disturbance frequency was increased to $St_D = 15.28$. For a first investigation at this frequency, the amplitude was reduced back to 200 percent. Figure 8 shows a typical instantaneous flow field in the form of isolevels of total vorticity.

As for Case 2, the structures that appear farther away from the base are weaker than for the *natural* wake. In addition, the vorticity distribution immediately downstream of the base shows a very strong accumulation of vorticity. The peaks of vorticity are much higher than for case 2, even though the disturbance amplitude is the same for both cases.

From video animation, it appears that the flow field immediately downstream of the base is dominated by the zero-mass jet and appears to be almost steady. This, however, is an artifact of the picture frames. Every frame was taken at a fixed point within the period of the disturbance. Thus, the flow field in the immediate vicinity of the base is periodic with the disturbance frequency. This was not observed for the lower frequency in Cases 1-3. However, the flow field farther downstream is still unsteady, with a much lower frequency than that of the disturbances introduced.

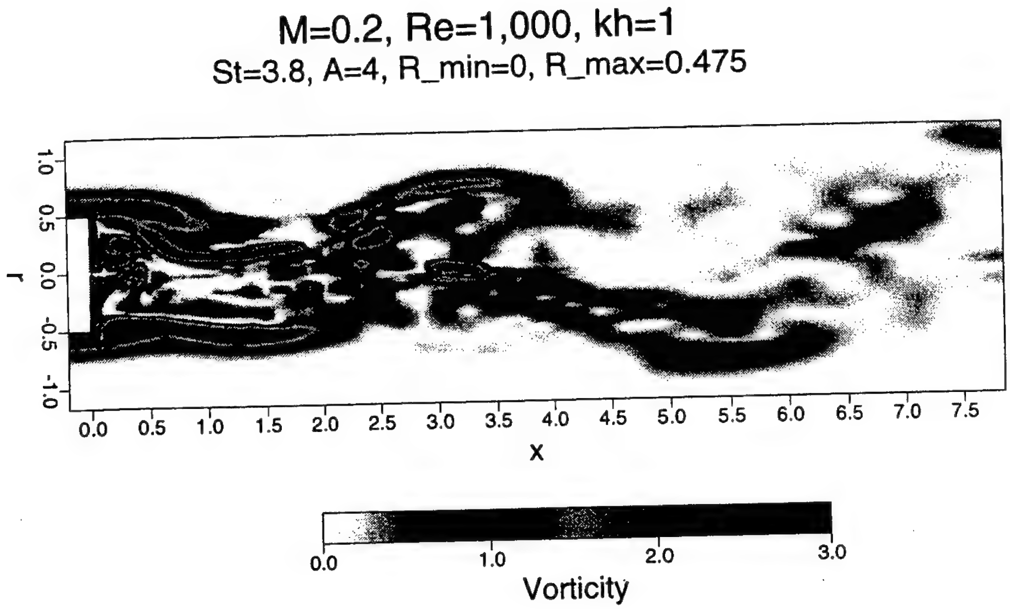


Figure 7. Isolevels of instantaneous total vorticity for case 3.

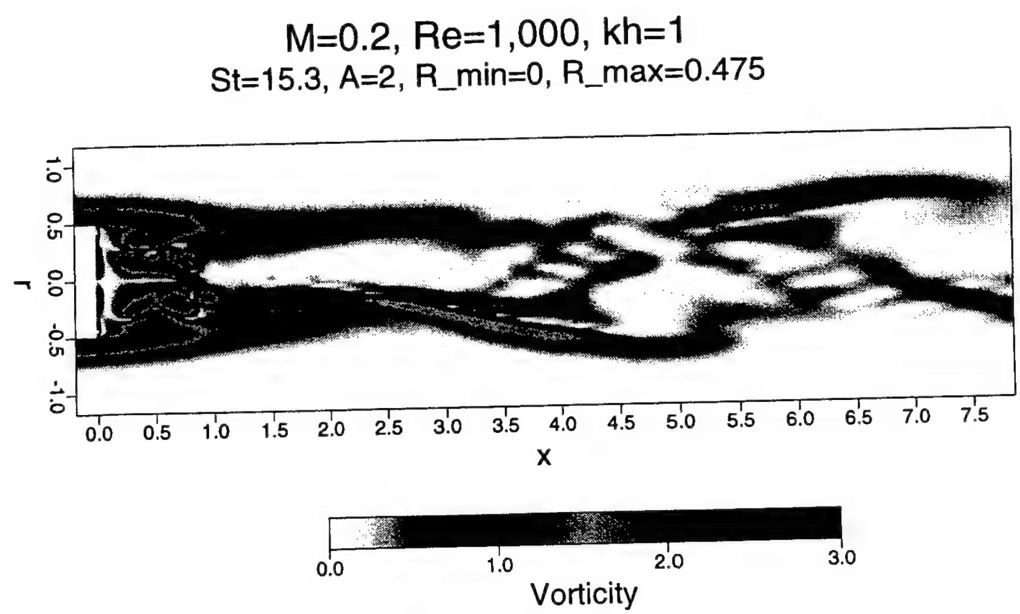


Figure 8. Isolevels of instantaneous total vorticity for Case 4.

3.2.5 Case 5

The same disturbance frequency as in Case 4 was used in this simulation. Now, however, the disturbance amplitude was doubled, resulting in a maximum velocity amplitude of about 400 percent of the free stream velocity. Figure 9 shows a typical instantaneous flow field in the form of isolevels of total vorticity.

No unsteady vortical structures were visible in Figure 9. The video reveals that the flow field is steady, with the exception of the immediate vicinity of the base. In addition, the numerical data show that the energy in the first azimuthal Fourier mode has dropped by two orders of magnitude by the time the simulation was terminated. Since the energy for this Fourier mode was still decaying, it is believed that the simulation would reach an axisymmetric steady state if continued (periodic near the base).

Figure 9 shows that, at this stage, there is a very strong jet embedded in the wake region that significantly alters the mean flow away from a typical wake flow profile. To further strengthen this point, the time-averaged flow field was determined. The results are shown in Figure 10 in the form of isolevels for axial velocity, radial velocity, pressure, and azimuthal vorticity. The axial velocity distribution clearly shows that there is a very strong jet present within the wake. In some regions, the center velocity is even larger than the free stream velocity. An integral analysis of the whole flow field might show that the drag is negative for this case. Or, in other words, the high-frequency disturbance could be creating a thrust. However, the energy that needs to be used for this type of disturbance is probably very high, and use of such a device for propelling a vehicle would not be very efficient.

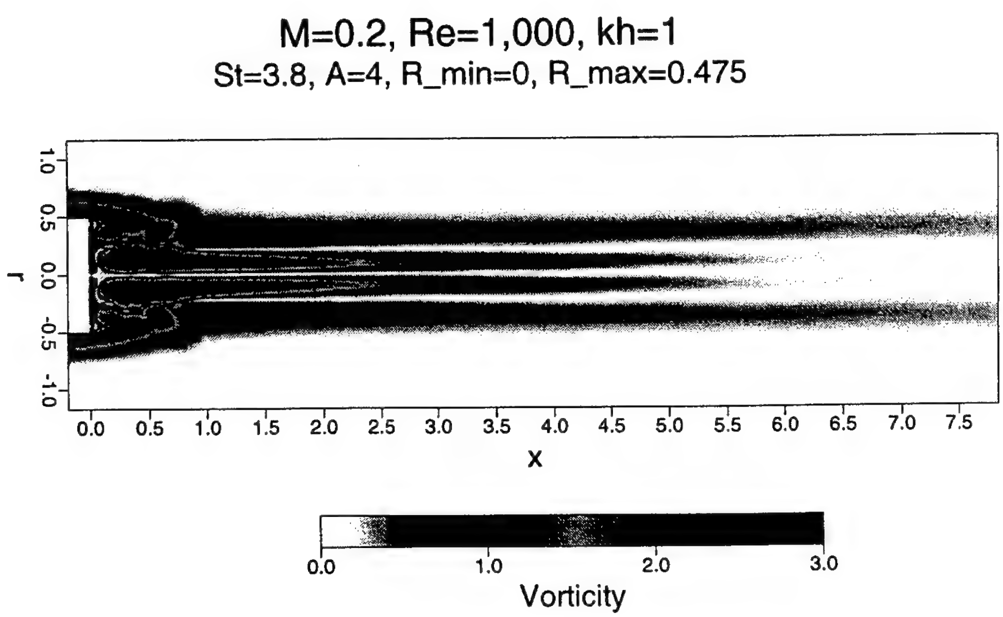
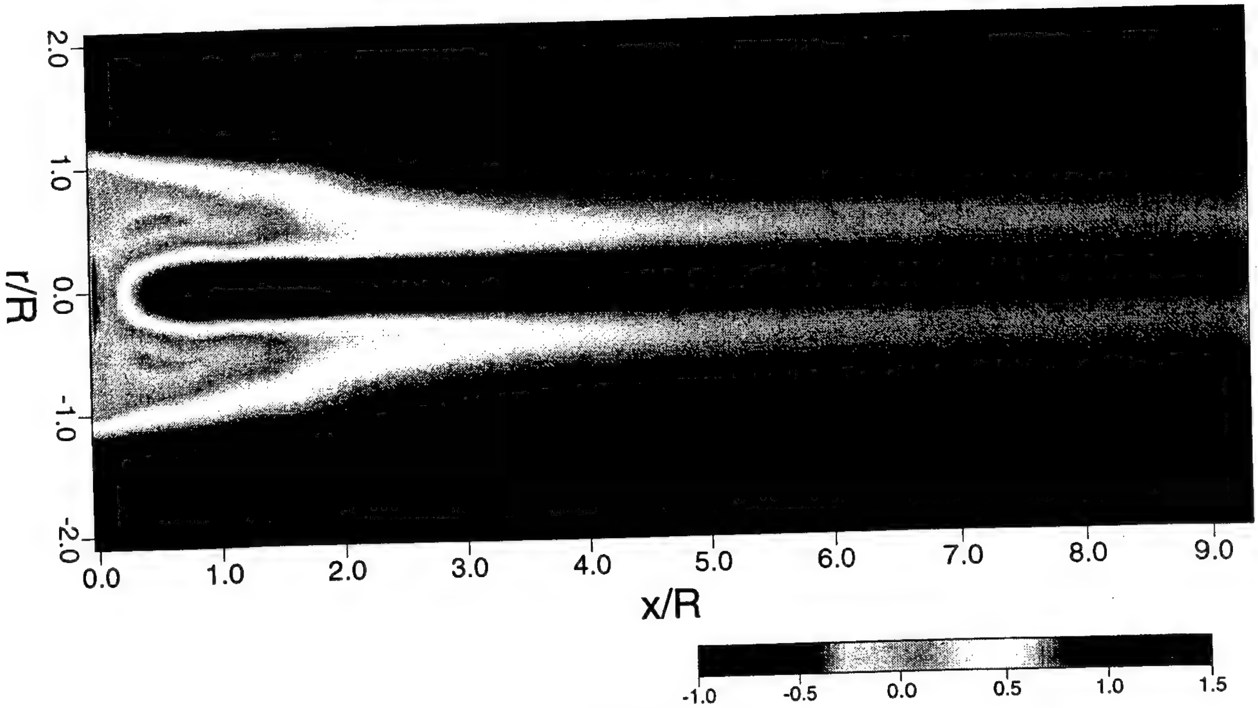
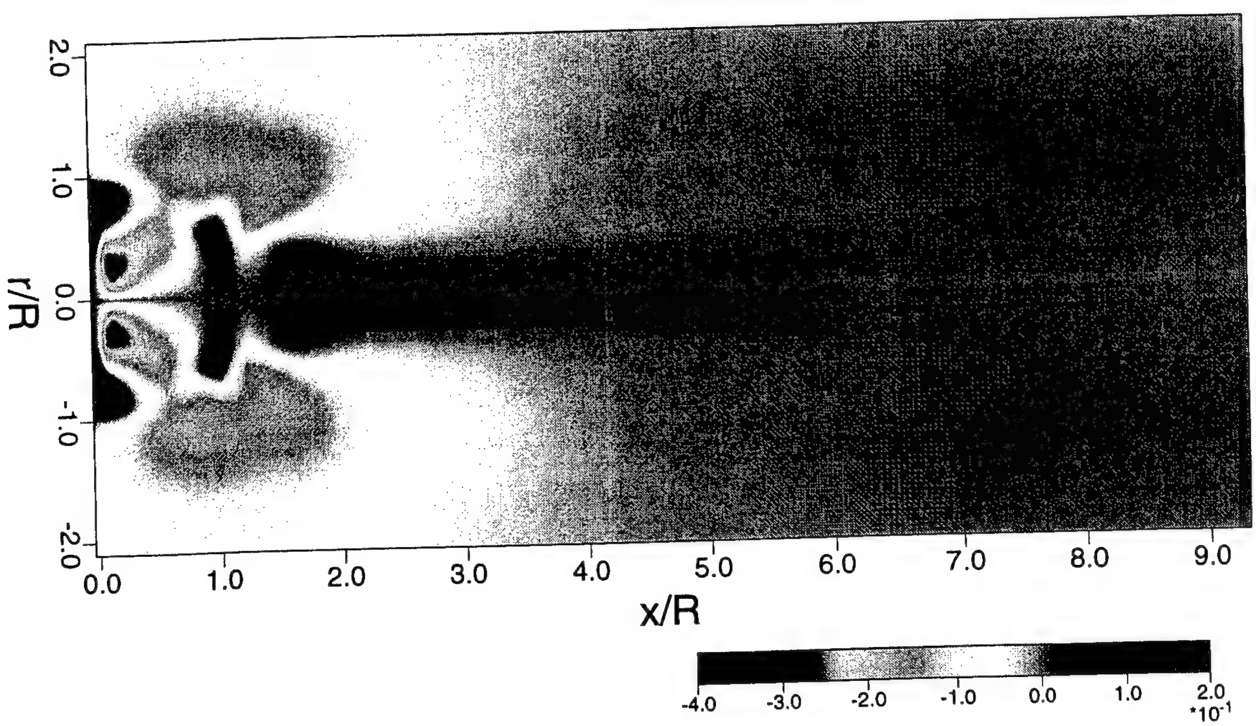


Figure 9. Isolevels of instantaneous total vorticity for case 5.



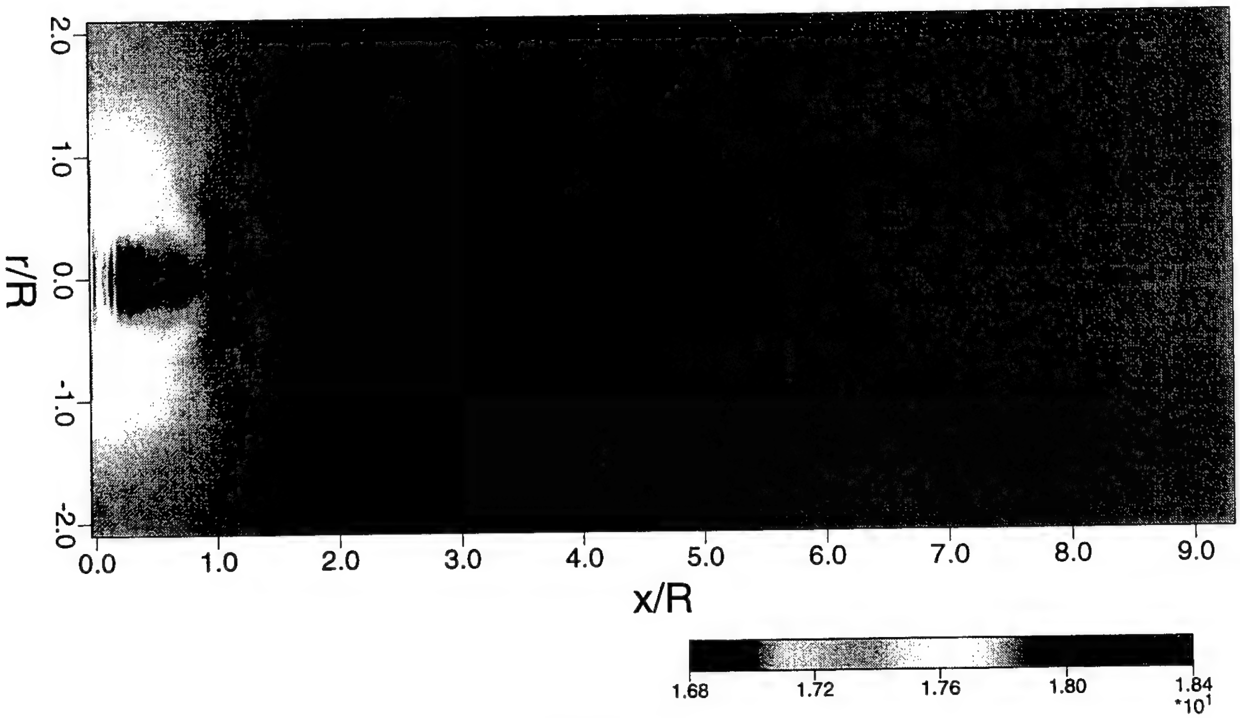
(a) Axial Velocity



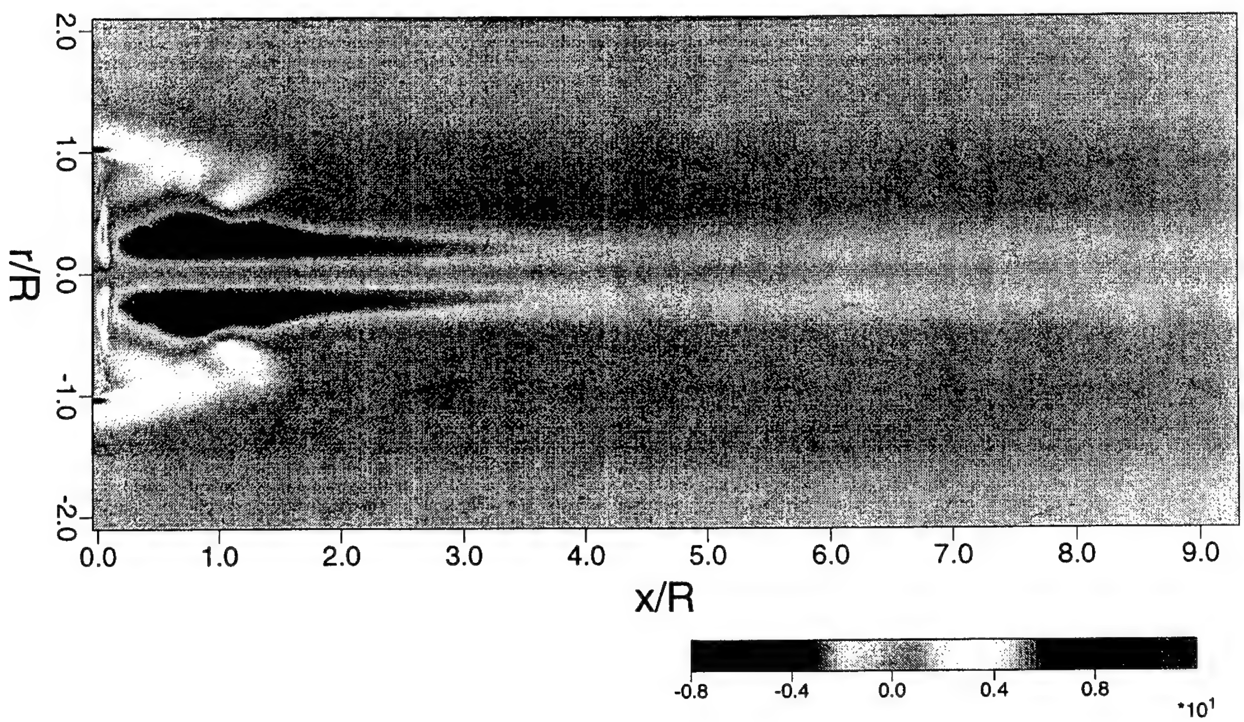
(b) Radial Velocity

Figure 10. Time averaged flow field for case 5.

Figure 10 (continued).



(c) Pressure



(d) Azimuthal Vorticity

3.2.6 Case 6

A slightly lower disturbance frequency than used in Cases 4 and 5 was used in this simulation. The disturbance amplitude was the same as that in Case 5, a maximum velocity amplitude of 400 percent of the free stream velocity. In addition, the blowing and suction area spanned only half the diameter. Figure 11 shows a typical instantaneous flow field in the form of isolevels of total vorticity.

In this case, the flow field does not reach a steady state, but reaches a periodic state. The Strouhal number of the periodic state is slightly higher than the peak of the natural oscillations ($St_D = 0.177$).

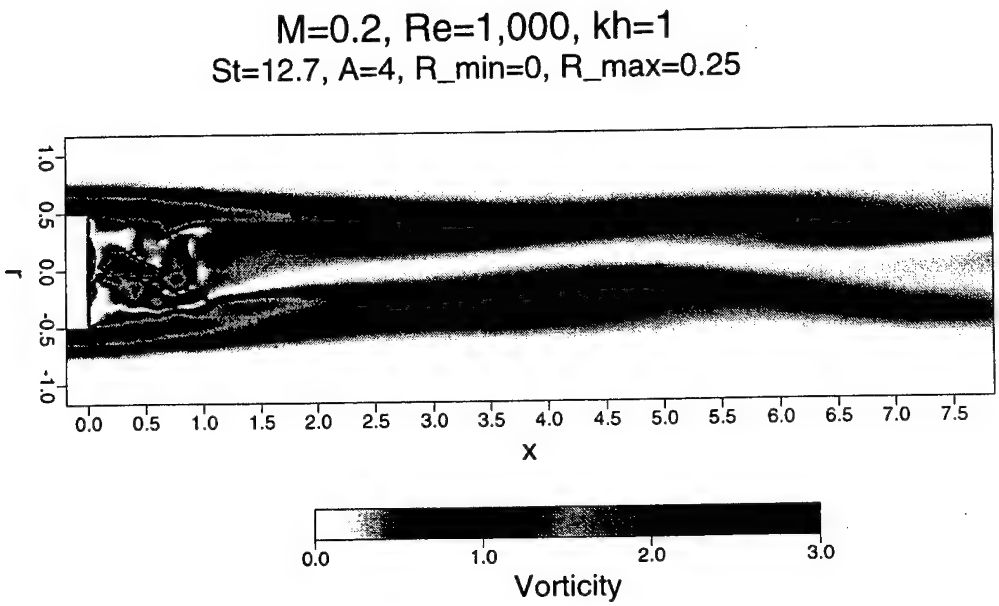


Figure 11. Isolevels of instantaneous total vorticity for Case 6.

4. CONCLUSIONS

For a Mach number of 0.2, six different cases with high axisymmetric high-frequency forcing (zero-mass jets) have been investigated. The frequency of the disturbances varied from $St_D = 3.82$ to $St_D = 15.28$ and the amplitudes were 200 to 400 percent of the free stream velocity. The results show that annular disturbances are less effective than centered disturbances (at least for the $St_D = 3.82$ cases). For the lower frequencies, it was found that the large disturbance amplitudes increase the level of disturbance energy in the flow field and, thus, most likely increases the base drag. The lower amplitude level for the same frequency, however, showed a decrease in the vorticity peaks of the vortical structure, which could indicate a decrease in disturbance energy and thus in the drag.

However, for the highest frequencies, the large disturbance amplitude resulted in an axisymmetric flow field. Thus, the introduction of the disturbances caused the unsteady three-dimensional structures to vanish completely. In addition, the time-averaged flow field revealed that the zero-mass jet most probably results in a significant reduction of base drag.

In future work, different disturbance profiles should be investigated, such as a parabolic profiles over the disturbance slot. Such profiles are likely to produce stronger vortices that result in larger induced velocities. In addition, other frequencies, amplitudes, and slot sizes should be investigated in the form of a parameter study in order to obtain a better idea of a possible optimum for this type of disturbance generation.

In addition to the simulations for the axisymmetric wake, analogous simulations were carried out for the two-dimensional wake. The effect of employing zero-mass jets was equally striking. With proper pulsing frequencies and amplitudes, all unsteady vortical structures in the wake could be eliminated. This striking effect of zero-mass jets remained intact for higher subsonic Mach numbers and even low supersonic March numbers ($M = 1.2$).

Attempts to extend the simulations to higher supersonic Mach numbers ($M = 2.5$) have not been successful yet. The reason for this is that very high frequencies are required for the pulsing at higher supersonic Mach numbers. As a consequence, the local velocities close to the actuators reach very high (supersonic) velocities and unsteady shock waves emanate from the actuators. These unsteady shock waves are difficult to handle numerically, in particular, with regard to their interaction with the free stream boundary of the computational domain. Therefore, more code development work would be required to allow investigations of zero-mass jets for higher supersonic Mach numbers.

In summary, the results of the present investigations indicate that zero-mass jets may be effective for reducing the base drag for wake flows and that these effects may also be present for supersonic flows. However, further investigations would be required to substantiate these claims.

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